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Towards Hybrid Energy Systems Bottom-up Models:

Incorporating macro-economic and behavioural drivers

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Expert Workshop on Energy and Climate Modeling

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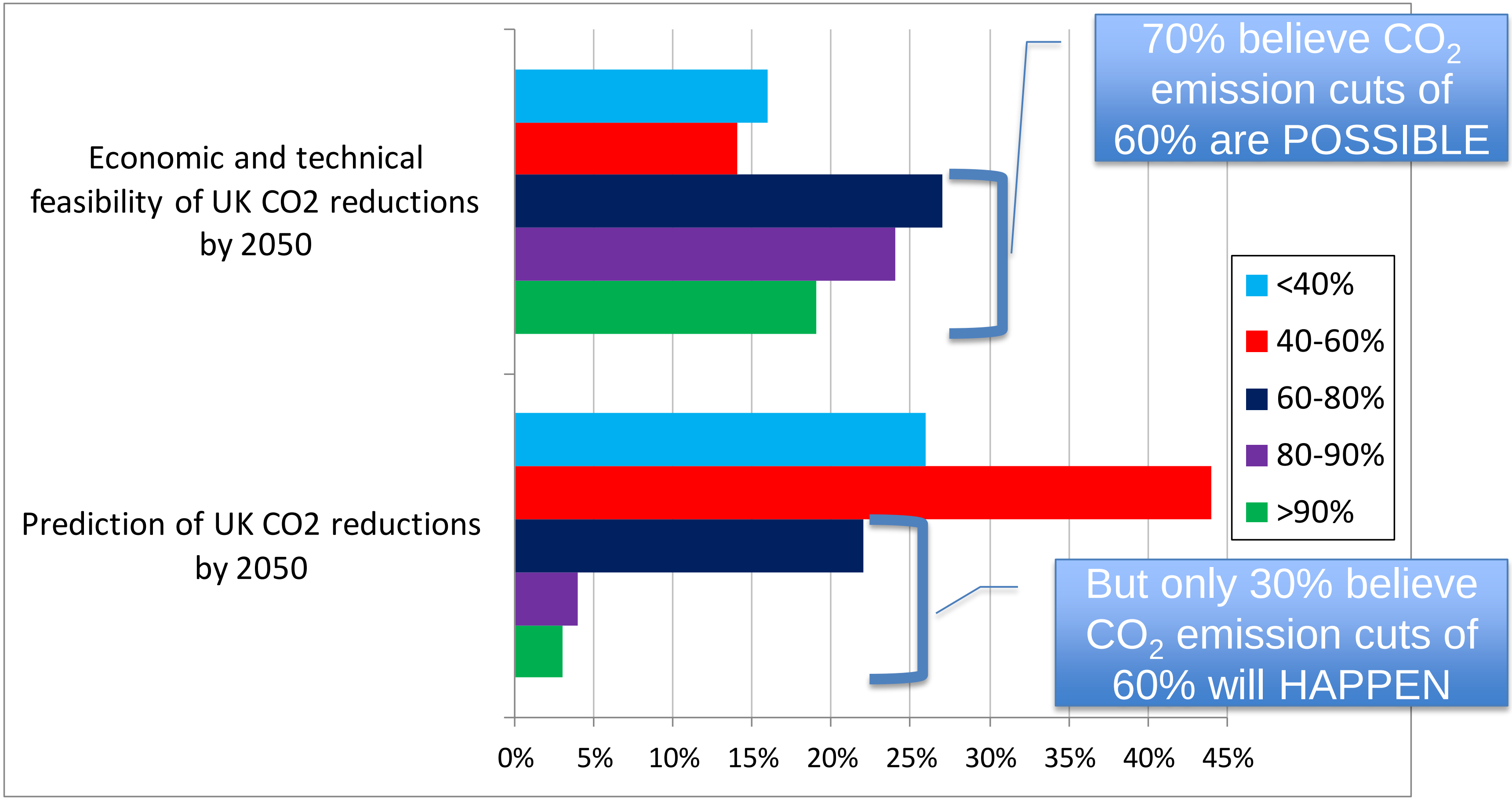
Expert assessment of long-term UK CO_2 reductions
[Source: UKERC Energy 2050 launch, 2009]



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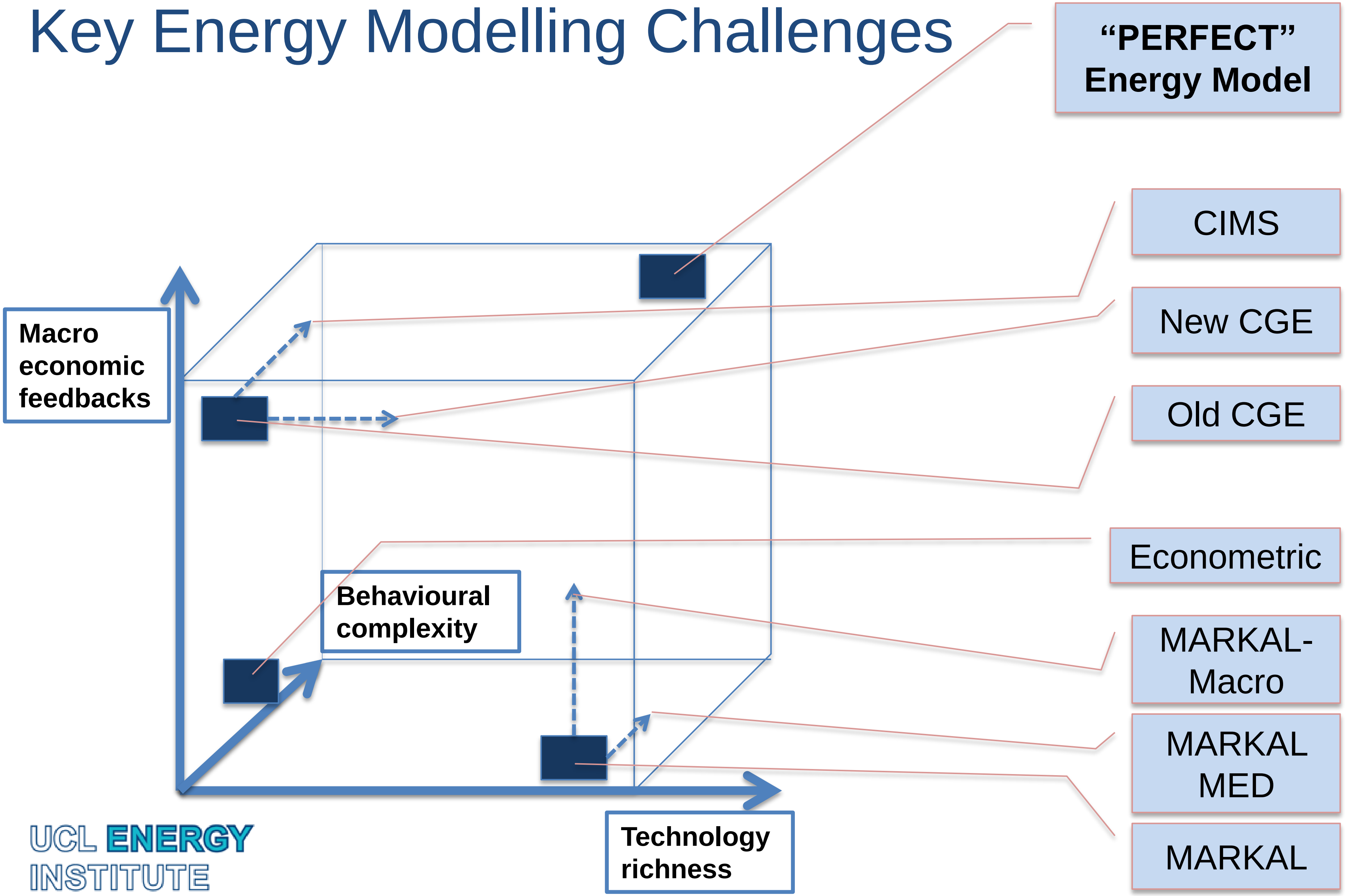
Outline

- Two topics that are key in improved bottom-up energy modelling
  - Improved representation of behavioural complexity
  - Improved representation of macro-economic interactions
    - UK MARKAL-Macro description
    - UK MARKAL-Macro outputs

Key Energy Modelling Challenges



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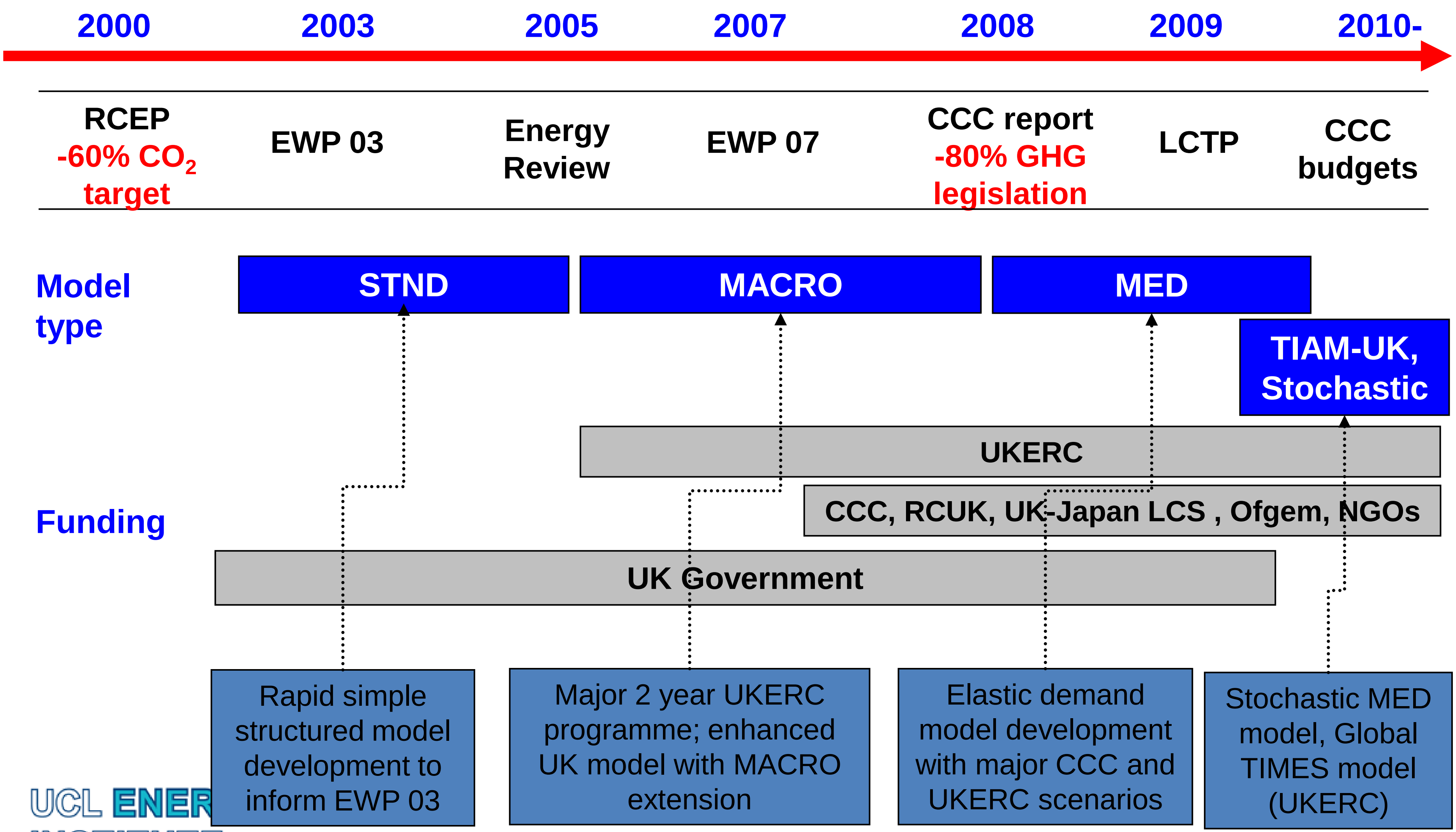
MARKAL modelling for UK policy



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Bottom up models and behavioural complexity

- MARKAL Elastic Demand (MED)
  - Scenario analysis for alternate energy service demands (ESDs)
  - Own price elasticities (η_p) for individual ESD
    - $\eta_p = {}^{\textbf{\% change in ESD quantity}} / {}_{\textbf{\% change in price}}$
    - Range from 0.25 - 0.61 depending on ESD
  - Cross price elasticities (η_x) between ESDs (e.g., car vs. bus)
  - Implied hurdle rates for end-use technologies
    - Range from 5% - 25% (but can be much higher from historical uptake)
  - Constraints on end-use technology deployment
- BUT
  - How to include non-cost drivers into a cost optimisation approach?
  - Perfect foresight assumption (vs. myopic)
  - Calibration of parameters (revealed vs. stated preferences)

Simulation modelling of behaviour

$$MS_j = \frac{\left[CC_j * \frac{r}{1-(1+r)^{-n}} + MC_j + EC_j + i_j \right]^{-v}}{\sum_{k=1}^{K} \left\{ \left[CC_k * \frac{r}{1-(1+r)^{-n}} + MC_k + EC_k + i_k \right]^{-v} \right\}}$$

- Where:
  - Market heterogeneity (v)
  - Intangible costs/benefits (i)
  - Hurdle rates (r)
  - Capital costs (CC), operational costs (MC), fuel costs (EC), lifetime (n), for new technology (j) or competing stock of technologies (k)
- Plus additional parameters:
  - Replacement/retrofitting rate (b)
  - Demand elasticities (η)
  - Learning rates (l) - applied to capital cost and/or to behavioral parameters

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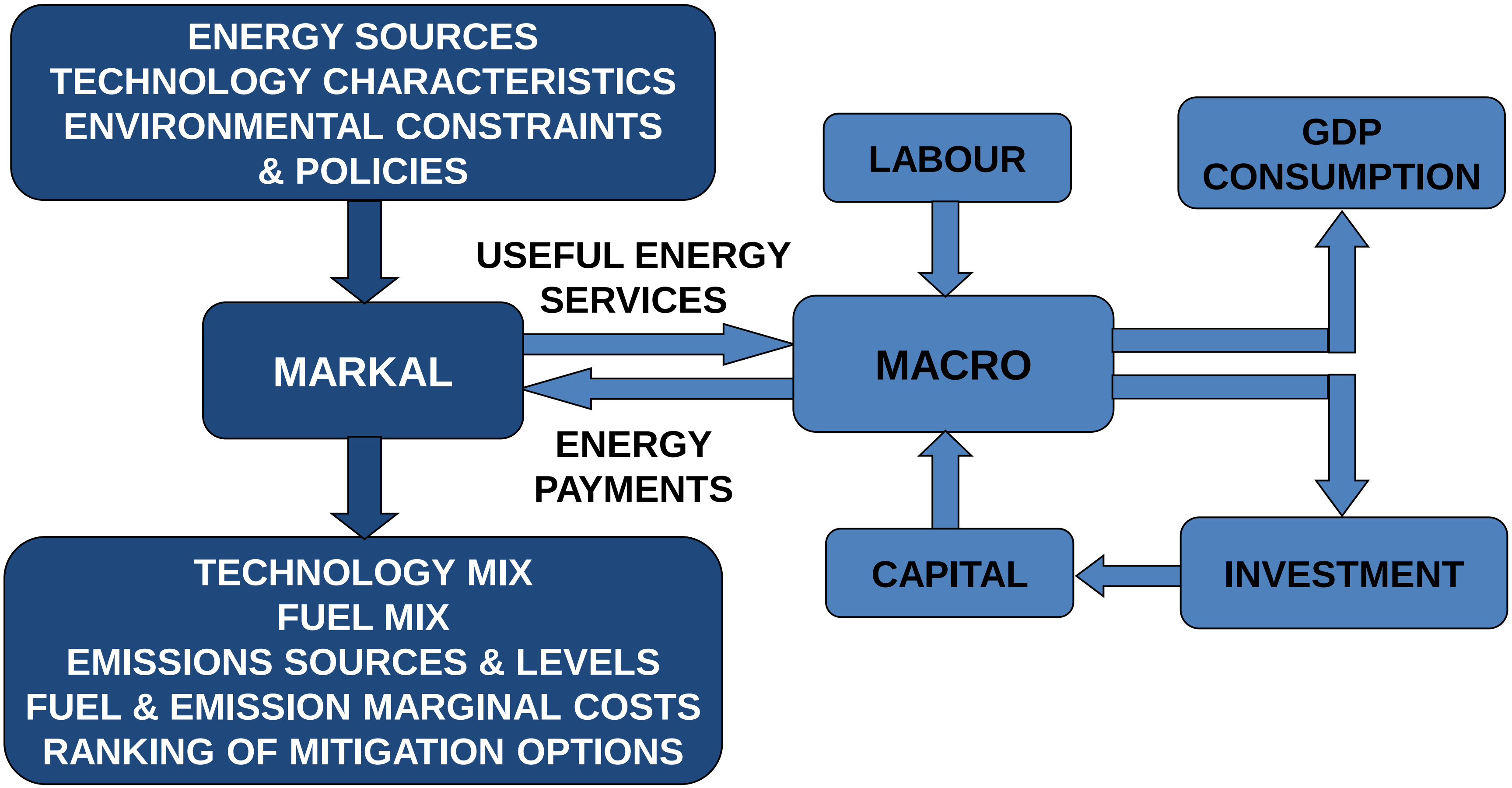
Overview of UK MARKAL-Macro (M-M)

- A **least cost optimization** model based on life-cycle costs (2000-2050) of competing technology pathways (to meet **energy demand services)**
  - **maximises overall discounted utility** (includes minimising energy system costs)
- **Assumes** rational decision making, perfect information, competitive markets
- **Technology** rich bottom-up model
  - Conservation, end-use technologies, electricity & heat conversion, refineries and bio/H_2/nuclear chains, domestic and imported fuels, infrastructures
- An **integrated energy systems** model
  - Energy carriers, resources, processes, electricity/CHP, end-use sectors (industry, services, residential, transport, agriculture), emissions, taxes/subsidies, demands (ESD)
- Physical, economic and policy **constraints** to represent UK energy system and environment
- Hard-link to single sector **macro-economic module**
- **Behavioural change** via aggregate ESD response, hurdle rates, constraints
- Model and data **validation** and documentation (www.ukerc.ac.uk)

UK MARKAL Macro (M-M) model



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M-M equations

$$\text{Utility} = \sum_{t=1}^{T-1} (\text{udf}_t)(\log\ C_t) + (\text{udf}_T)(\log\ C_T)/[1-(1-\text{udr}_T)^{\text{ny}}]$$
$$\text{udf}_t = \prod_{t=0}^{t-1} (1-\text{udr}_t)^{\text{ny}}$$
$$\text{udr}_t = (\text{kpvs})/\text{kgdp} - \text{depr} - \text{grow}$$

$$Y_t = C_t + I_t + \text{EC}_t$$

$$Y_t = \left[\text{akl}(K_t)^{\rho\alpha}(L_t)^{\rho(1-\alpha)} + \sum b_{\text{dm}}(D_{\text{dm},t})^{\rho}\right]^{1/\rho}$$
$$L_0 = 1,\ L_t = (1+\text{grow}_{t-1})^{\text{ny}} L_{t-1}$$
$$\rho = 1 - 1/\text{ESUB}$$

$$[Y/D_{\text{dm}}]^{1-\rho} * b_{\text{dm}} = \text{price}(\text{ref})_{\text{dm}}$$

$$K_{t+1} = \text{tsrv}K_t + (\text{ny}/2)(\text{tsrv}I_t + I_{t+1})$$
$$\text{tsrv} = (1-\text{depr})^{\text{ny}}$$
$$I_0 = (\text{grow}_0 - \text{depr})K_0$$

$$K_t(\text{grow}_t + \text{depr}) \leq I_t$$

Further detail

- Strachan N. and R. Kannan (2008) *Hybrid Modelling of Long-Term Carbon Reduction Scenarios for the UK*, Energy Economics, 30(6): 2947-2963
- Strachan N., S. Pye and N. Hughes (2008*) International Drivers of a UK Evolution to a Low Carbon Society*, Climate Policy, 8: S125-S139

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M-M features

- Macro-economic growth model hard-linked to a energy systems model
  - Explicit calculation of GDP, consumption and investment
  - Aggregated demand feedbacks from changes in energy prices
  - Autonomous demand changes for scenario analysis where energy demands are decoupled from economic (GDP) growth
  - Detailed technological change and energy interactions as before
- But…
  - No sectoral competitiveness and other trade issues
  - No information on transition costs
  - No revenue recycling from taxation or auctioning permits
  - Non-formal estimation of aggregated parameters (e.g. ESUB)
  - Consumer preferences are unchanging through the model horizon
- Hence, M-M gives lower bound on decarbonisation costs

Assumptions and Scenarios

- Model assumptions as per documentation
  - www.ukerc.ac.uk/support/tiki-index.php?page=ES_MARKAL_Documentation_2010)
  - International biomass imports limited to 1.1EJ per annum in 2050 (with linear path from 2000)
  - New nuclear generation is excluded
  - Includes international aviation (fuel use held at 2010 levels) plus a 2.5. multiplier for secondary warming impacts
  - Oil prices: range from $50-56/bl 2010-2020, rising to $69/bl by 2040
  - Gas prices: $5.4/MMBTU in 2015, then rise to $6.8/MMBTU by 2040
  - Coal rises from around $64.5/tonne in 2015, rising slowly to $73.3/tonne by 2040
- Core Scenario: MM C80
  - 80% absolute reductions (relative to year 2000) in UK domestic CO_2 emission by 2050
  - Equates to 123.6 $MtCO_2$ in 2050 (from 627.6 $MtCO_2$ in 2000)
- MM C80 LEARN
  - Accelerate learning rates for renewables, using European Commission World Energy Technology Outlook 2050 estimates
- MM C80 HighP
  - Oil at $90/bl in 2020, rising to $102/bl by 2040, with correspondingly higher gas and coal prices
- MM C80 EFF
  - Accelerated energy efficiency scenario via reduction in end-use ‘hurdle rate’ from 25% to 10%

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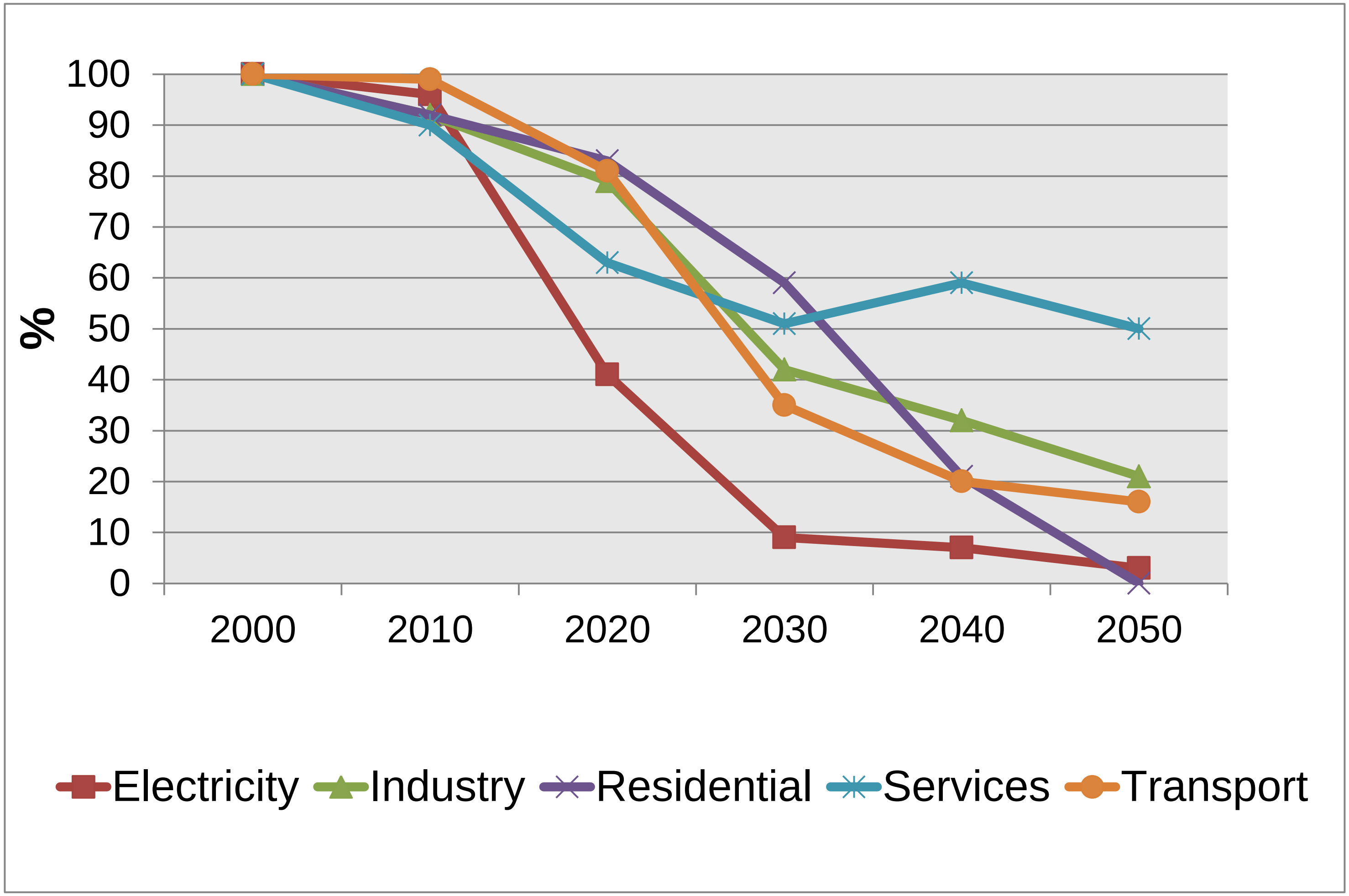
M-M C80: Decarbonisation by sector



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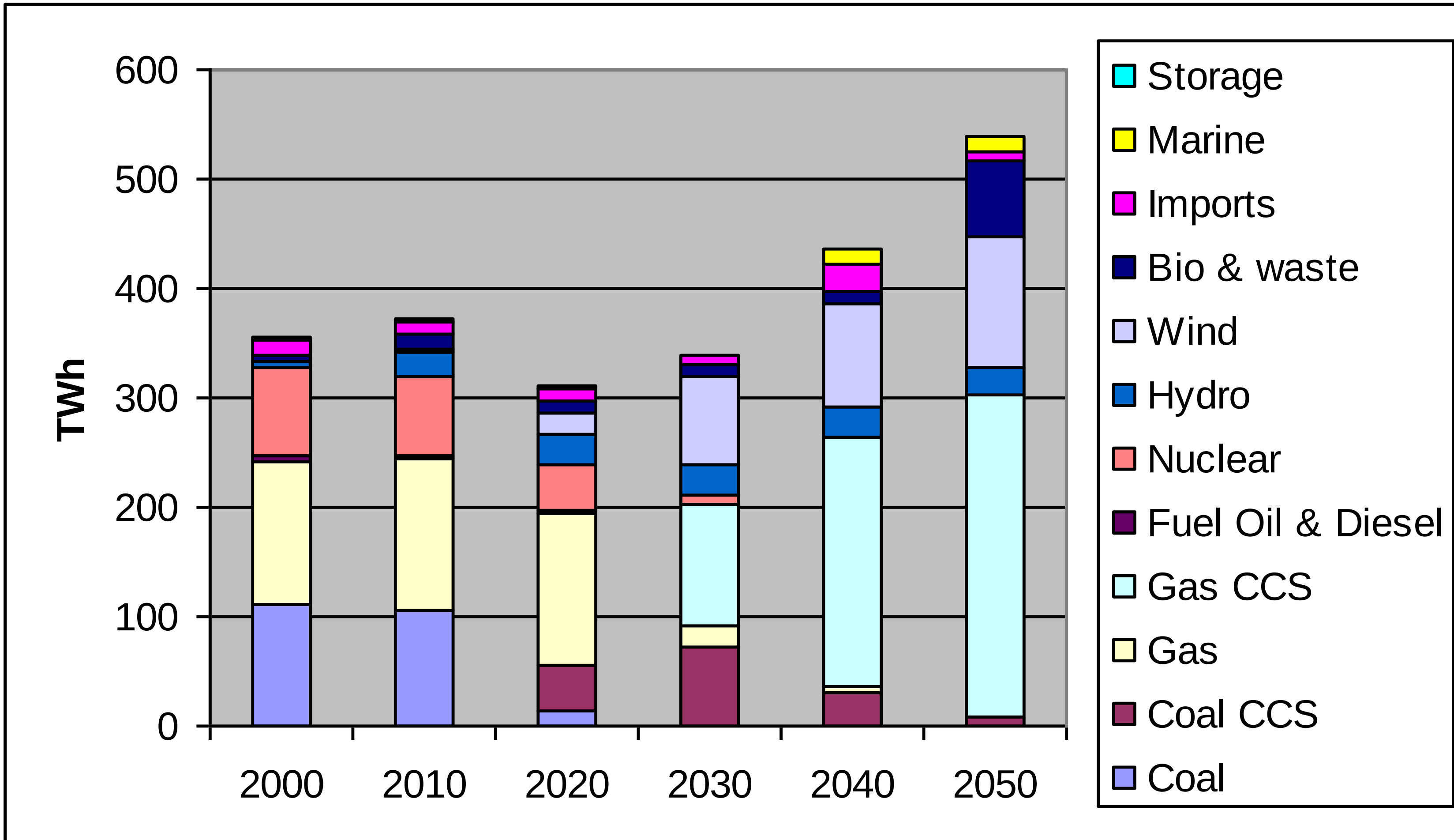
M-M C80: Electricity generation



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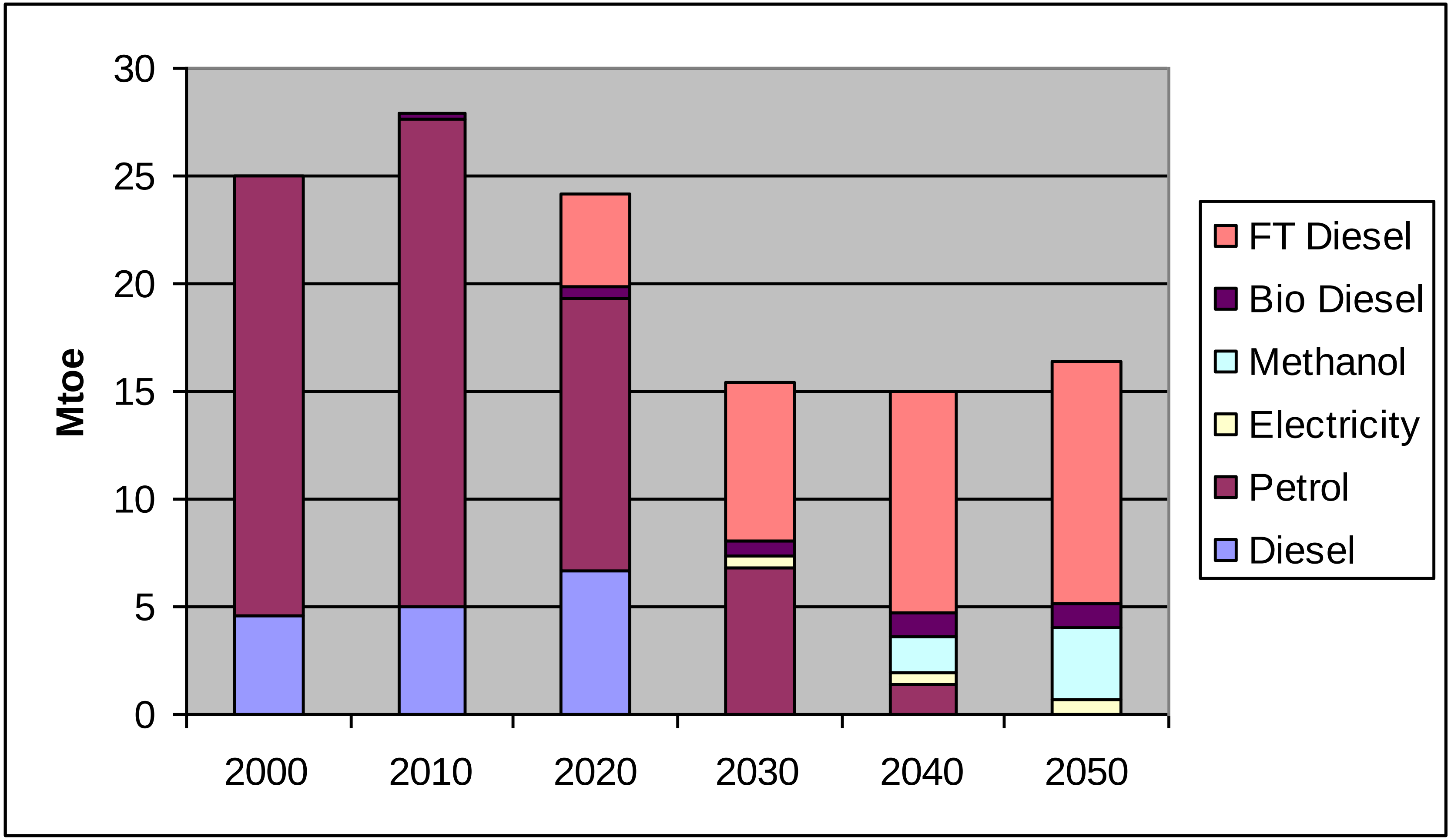
M-M C80: Fuel use in cars



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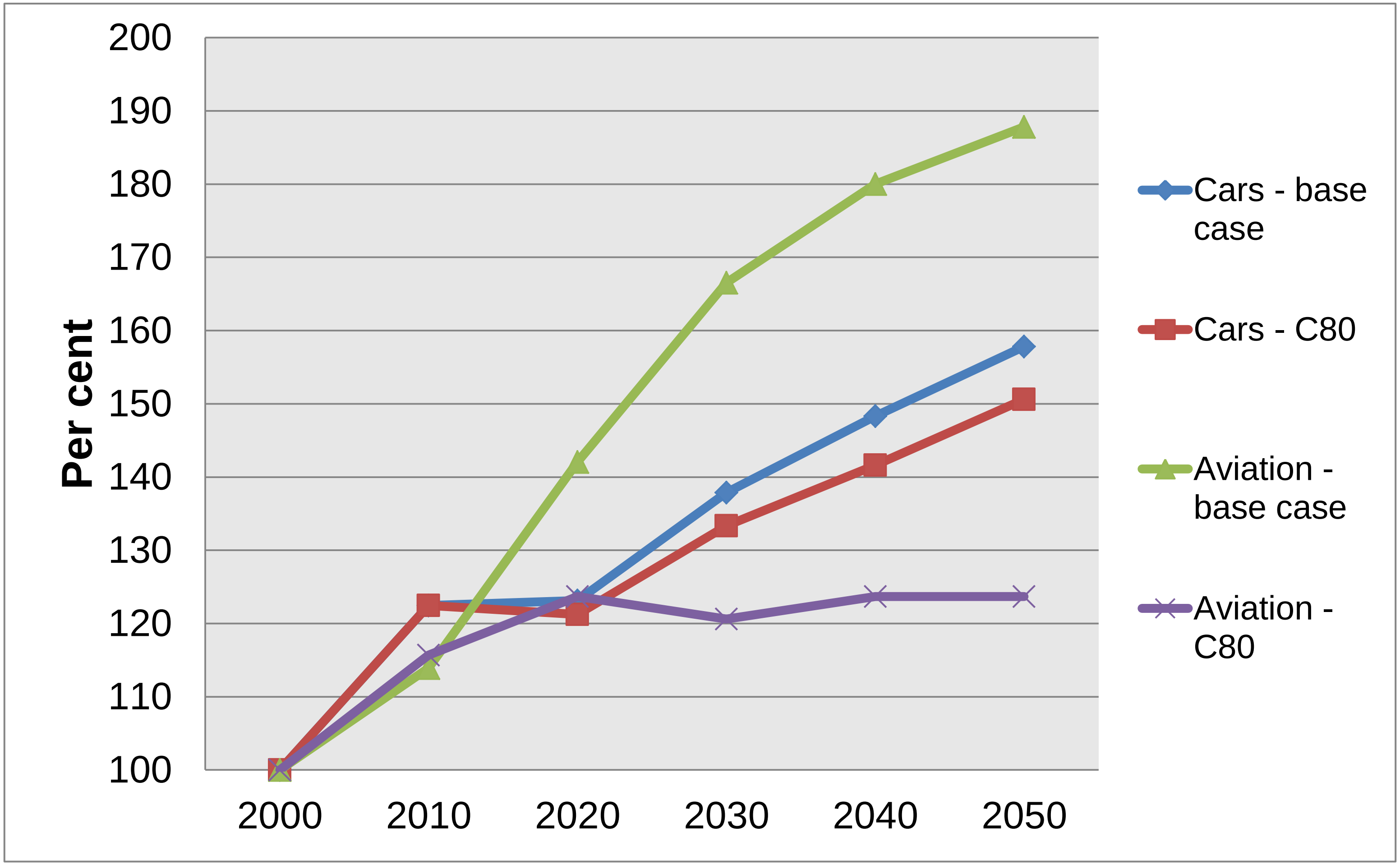
M-M C80: Transport service demand



M-M Scenarios: Macro-economic costs

Scenario	% of GDP			
	2020	2030	2040	2050
Central scenario	0.46	1.70	2.43	2.81
With accelerated technological change	0.45	1.60	2.35	2.58
With higher fossil fuel prices	0.45	1.54	2.27	2.64
With accelerated energy efficiency	-0.07	0.63	1.63	2.04

Costs in perspective

[Source: D MacKay, *Sustainability without the Hot Air*, Cambridge University Press]
All in 2010 US $

Expenditure	per year (B$/yr)	One time cost (B$)	per UK capita ($/yr)
UK GDP	2,250	-	37,500
UK GDP (2050)	4,970	-	82,800
-80% CO_2 GDP cost (2050)	101 - 140	-	1,680 - 2,330
Final energy consumption	120	-	2,000
UK Bank bailout	-	~ 800	13,330
Health budget	198	-	3,300
Education budget	93	-	1,550
BP*, Shell, Exxon profits	10 - 40	-	-
Nuclear decommissioning	-	73	1,220
New nuclear weapons	-	25	420
Public renewable energy R&D	0.019	-	0.3

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Conclusions

- Bottom-up technology-detailed energy systems models are developing toward hybrid energy models
  - Incorporate behavioural drivers
  - Incorporate macro-economic feedbacks, e.g., the hard-linked MARKAL-Macro model
- Case study: UK -80% CO_2 emission reduction scenarios
  - Radical technological transition required
  - Costs at 2-3% of GDP by 2050: substantial but manageable
- Alternate energy models give alternate insights
  - Consider soft-linking of models